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ALL SILICA FUME IS THE SAME, ISN'T IT…?

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14 October 2021

Distribution A: Approved for public release.

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What is silica fume?

- Byproduct of the production of silicon and ferrosilicon metals
- Pozzolanic material
- ASTM C1240 Specification
  - $SiO_2 \geq 85\%$
  - Specific Surface Area ≥ 15 m^2/g
- First use in concrete in the 1940s in Norway
- First domestic publication concerning silica fume was published by WES in the 1980s
- Two major forms commercially available today
  - Undensified
  - Densified

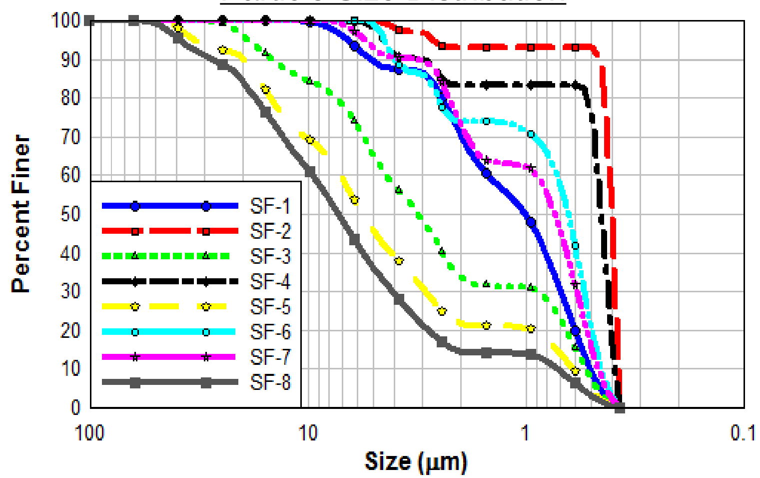
Initial Work

Preliminary study performed in 2015 by the ERDC looked at mass replacement of eight different silica fumes in a constant UHPC mixture proportion with highly variable results.

Chemical Characterization

Silica Fume	SiO_2 (%)	CaO (%)	MgO (%)	Na_2O (%)	Balance (%)	LOI (%)
SF-1	97.30	0.00	0.06	0.00	2.64	1.35
SF-2	95.04	0.01	0.38	1.79	2.79	1.39
SF-3	93.26	0.00	0.21	1.24	5.29	3.93
SF-4	74.95	17.90	2.89	0.52	3.74	0.89
SF-5	97.21	0.00	0.15	0.16	2.48	1.61
SF-6	96.06	0.00	0.14	0.12	2.68	2.73
SF-7	93.65	0.10	0.37	0.23	5.65	4.47
SF-8	97.42	1.27	0.09	0.01	1.21	0.93

Particle Size Distribution



Results

Property/Batch	SF-1	SF-2	SF-7
Time – min	14:45	6:15	9:15
Flow - %	57.6	60.6	82.1
ρ – kg/m^3	2372	2337	2390
f_c – MPa	186	185	205

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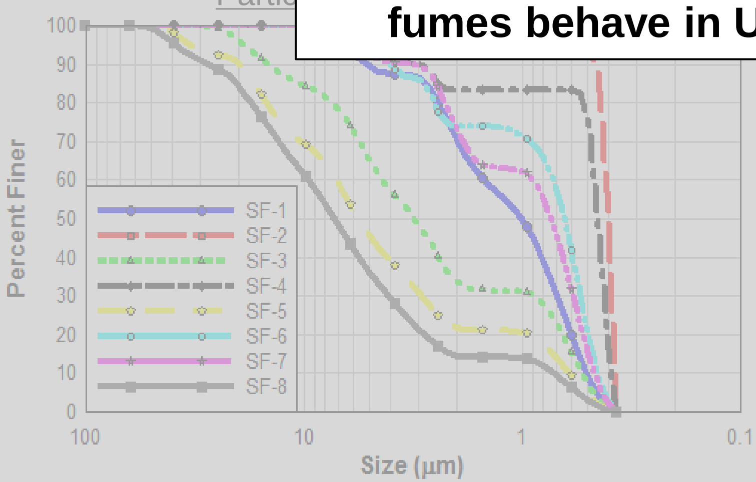
SF-3	93.26	0.00	0.21	1.24	5.29	3.93
SF-4	74.95	17.90	2.89	0.52	3.74	0.89
					2.48	1.61
					2.68	2.73
					5.65	4.47
					1.21	0.93

- **Why could only three of the silica fumes successfully be incorporated into the baseline mixture proportion?**
- **Are chemical or physical differences more important when understanding how different silica fumes behave in UHPC mixture proportions?**

Partic



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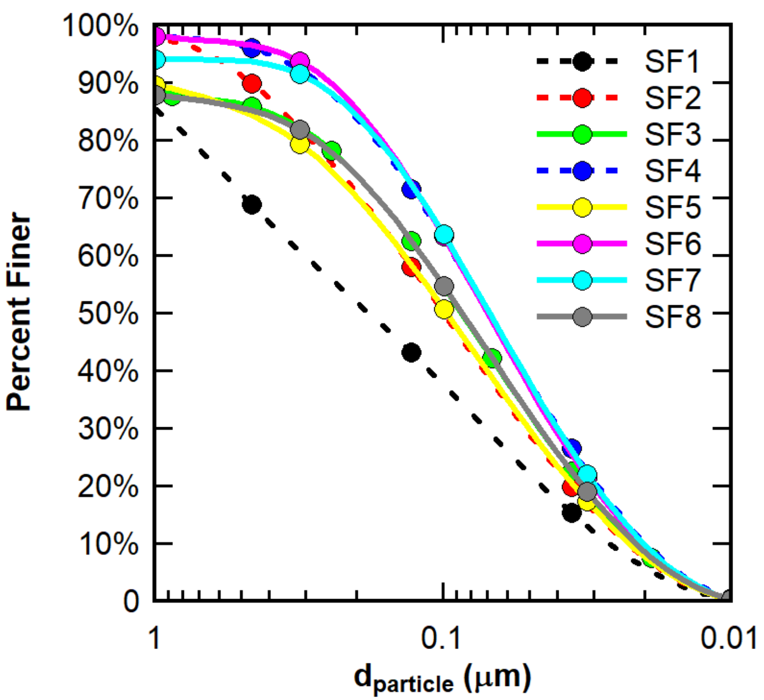
Materials Characterization

Physical Characterization of Silica Fume

Silica Fume	G_s	ρ_{bulk} (kg/m³)	SSA_{BET} (m²/g)	SSA_{PSD} (m²/g)
SF1	2.37	412	18.1	31.7
SF2	2.23	319	29.3	43.7
SF3	2.30	706	22.0	45.5
SF4	2.23	386	29.4	54.3
SF5	2.23	698	25.7	43.9
SF6	2.26	670	24.0	52.6
SF7	2.21	726	22.8	54.2
SF8	2.34	---[a]	19.8	44.8

[a]Due to limited material supply, ρ_{bulk} was not determined for SF8.



Chemical Characterization of Silica Fume

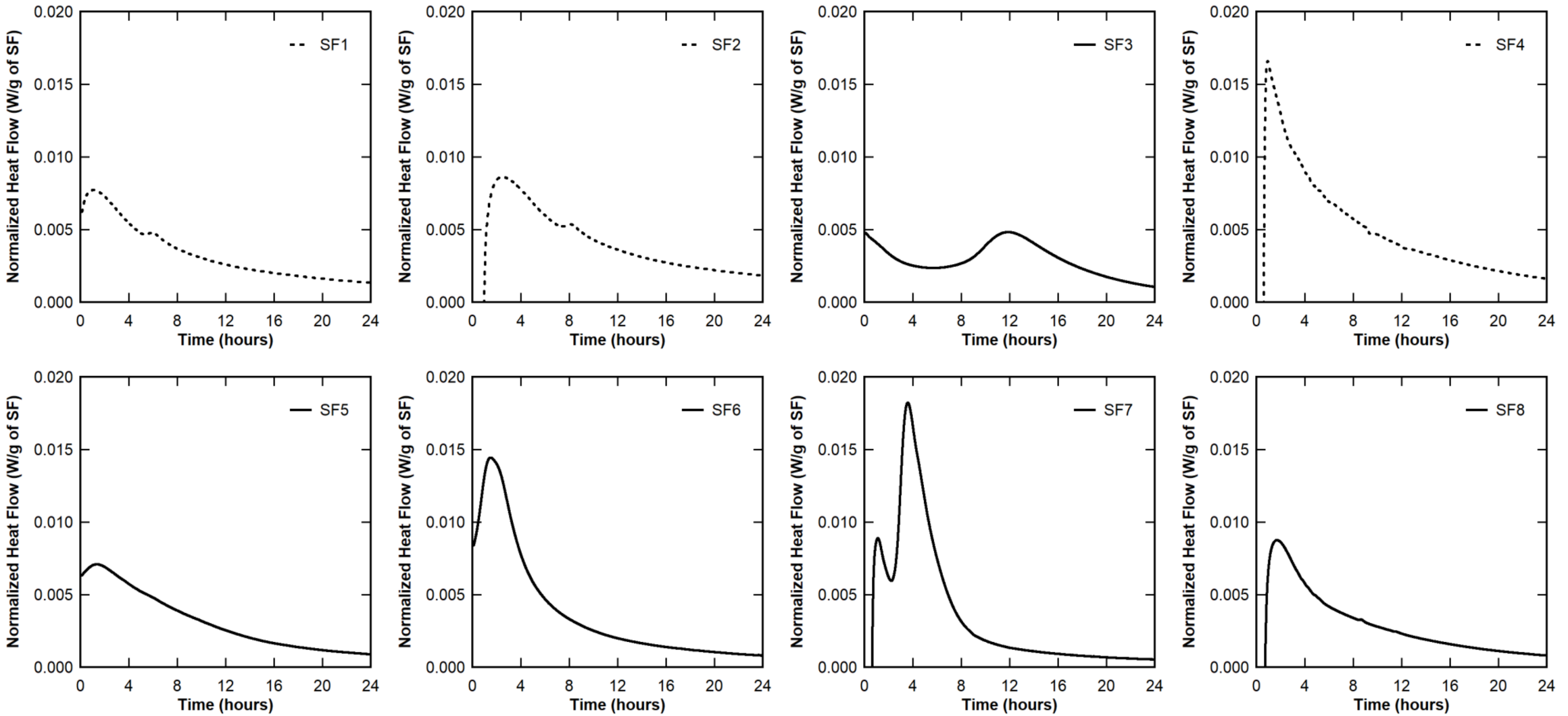
Silica Fume	SiO_2 (%)	CaO (%)	MgO (%)	Mn_2O_3 (%)	LOI (%)	Balance (%)[a]	Other[b]
SF1	92.2	1.5	0.2	2.2	0.9	3.0	ZrO_2
SF2	95.9	0.3	0.3	1.4	0.9	1.2	None
SF3	83.4	0.9	1.3	5.4	2.0	7.0	K_2O, ZnO
SF4	97.8	0.3	0.2	0.0	0.9	0.8	None
SF5	70.0	19.5	2.6	0.0	5.1	2.9	None
SF6	90.4	0.6	1.9	3.3	2.5	1.3	None
SF7	94.3	0.6	0.3	1.7	2.0	1.2	None
SF8	68.4	18.0	2.0	0.1	8.9	2.6	None

[a]Total content of other XRF phases

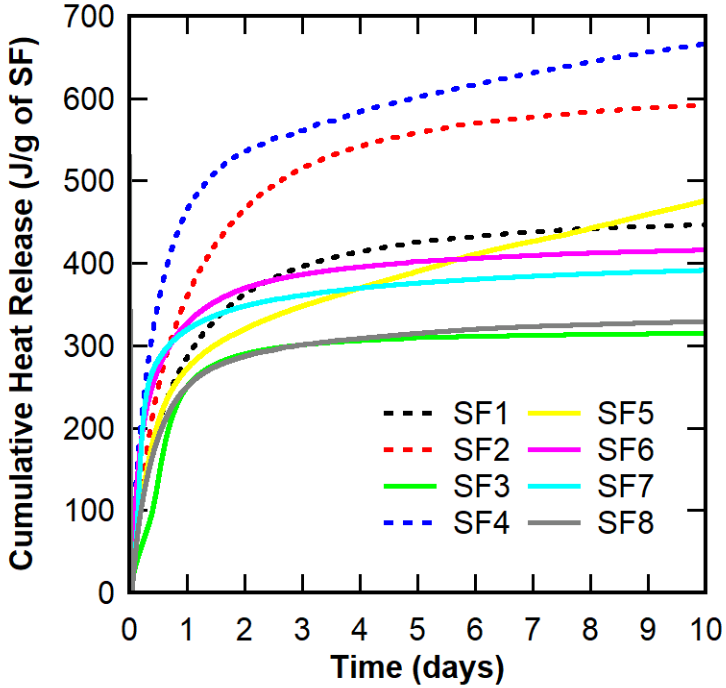
[b]Other XRF phases greater than 1%

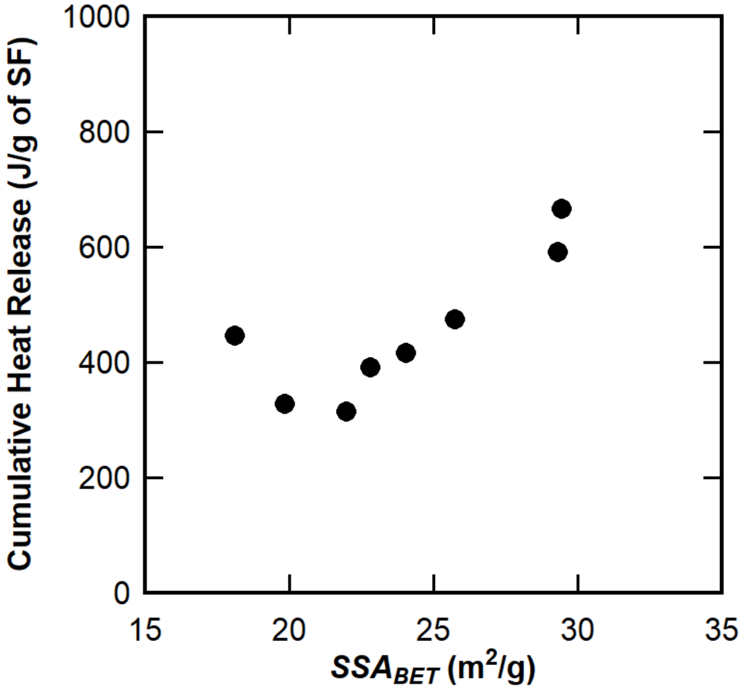
Silica Fume Reactivity

Silica Fume Reactivity



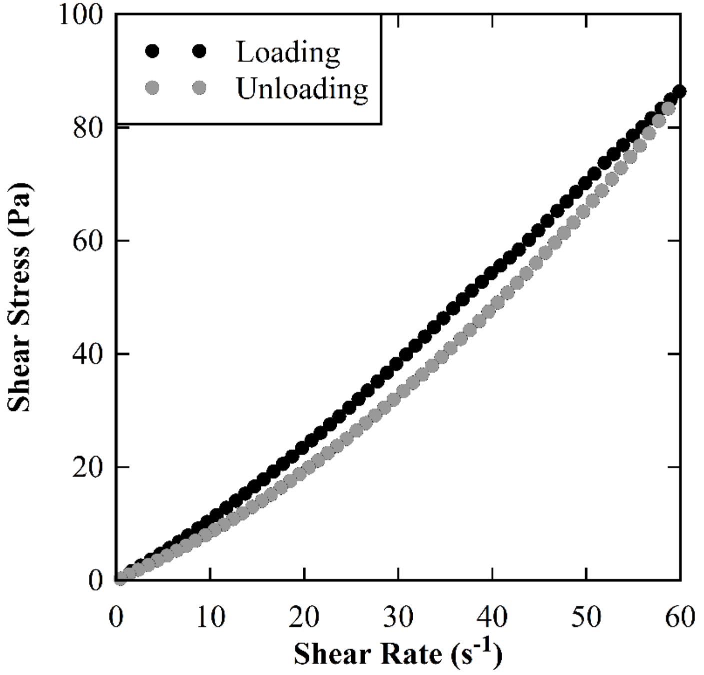
Silica Fume Reactivity





Rheological Effects

Rotational Rheology Experiments

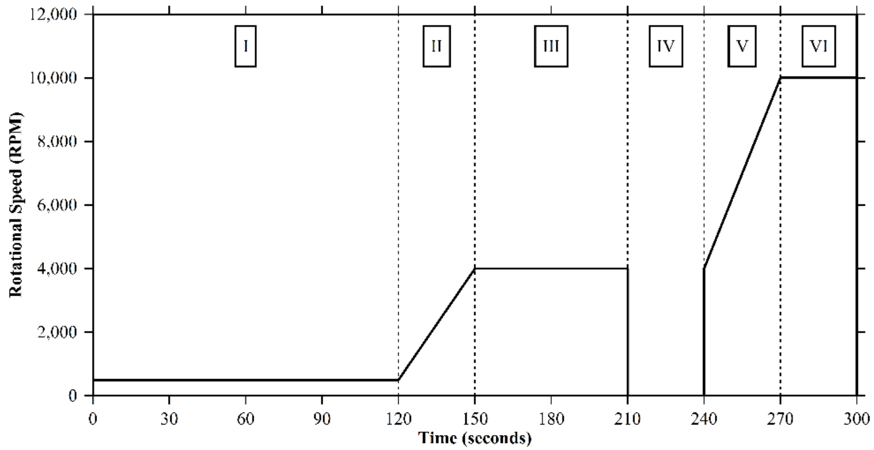


- Herschel-Bulkley model fit to unloading curve data

$$\tau = \tau_0 + k\dot{\gamma}^n$$

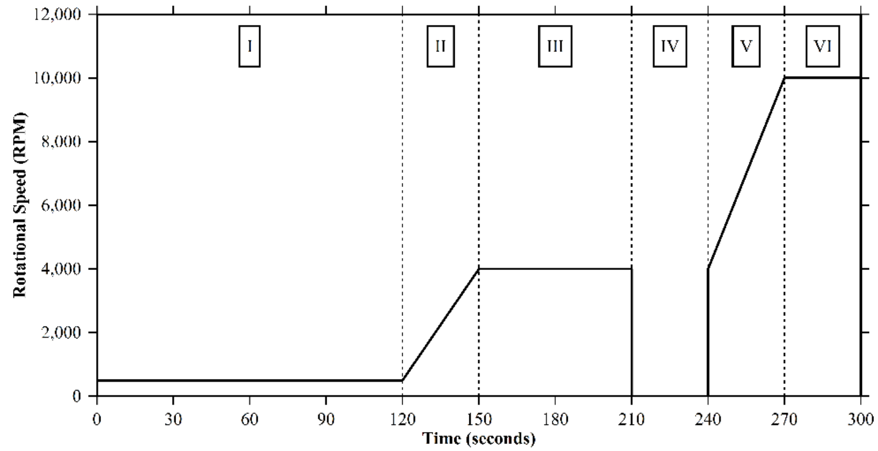
- τ = shear stress (Pa)
- τ_0 = yield stress (Pa)
- k = consistency (Pa·s^n)
- $\dot{\gamma}$ = shear rate (s^{-1})
- n = rate index

Rotational Rheology Experiments



Source	DF	SS	MS	F	P-value
A = Fume type	7	0.11	0.02	7.62	0.00
B = w/b	2	1.97	0.98	460.97	0.00
C = Fume amount	2	0.82	0.41	191.83	0.00
AB	14	0.09	0.01	3.09	0.01
AC	14	0.06	0.00	1.91	0.07
BC	4	0.22	0.06	26.09	0.00
Error	28	0.06	0.00	—	—
Total	71	3.33	—	—	—

Rotational Rheology Experiments



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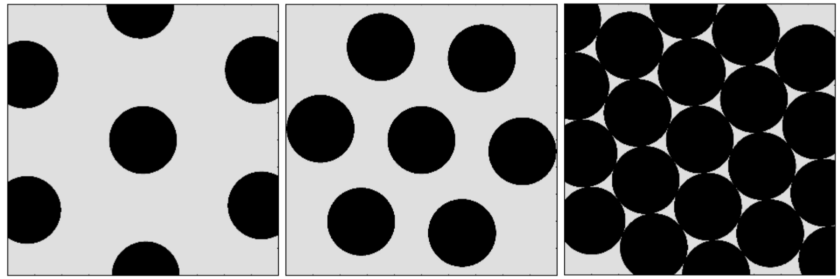
Water Thickness Model



$$m_{water,total} = \sum_{i=1}^{n} m_{water,reaction,particle\ i} + \sum_{i=1}^{n} m_{water,absorption,particle\ i} + m_{water,free}$$

$$m_{water,total} = \cancel{m_{water,reaction,cement}} + m_{water,absorption,silica\ fume} + m_{water,free}$$

$$m_{water,free} = m_{water,total} - m_{water,absorption,silica\ fume}$$

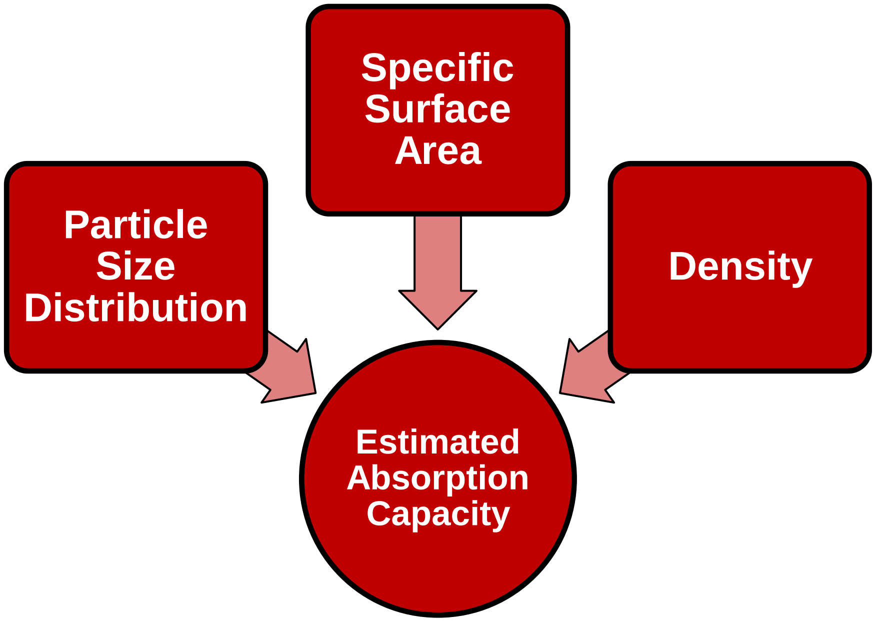
$$m_{water,free} = m_{water,total} - a m_{silica\ fume}$$

$$V_{water,free} = \frac{m_{water,total} - a m_{silicafume}}{\rho_{water}}$$

$$\boxed{t_{flow} = \frac{V_{water,free}}{A_{surface,system}}}$$

Estimating Absorption Capacity

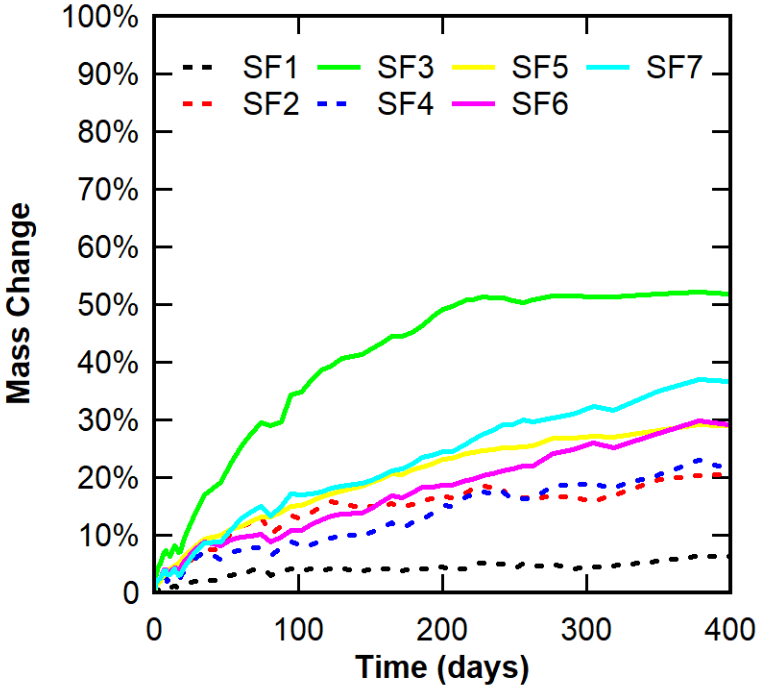
Approach #1 – Statistical Approximation



Silica Fume	G_s	SSA_{BET} (m^2/g)	a_{SA} (%)
SF1	2.37	18.1	18.1
SF2	2.23	29.3	14.8
SF3	2.30	22.0	22.4
SF4	2.23	29.4	20.5
SF5	2.23	25.7	18.6
SF6	2.26	24.0	24.0
SF7	2.21	22.8	26.2
SF8	2.34	19.8	23.8

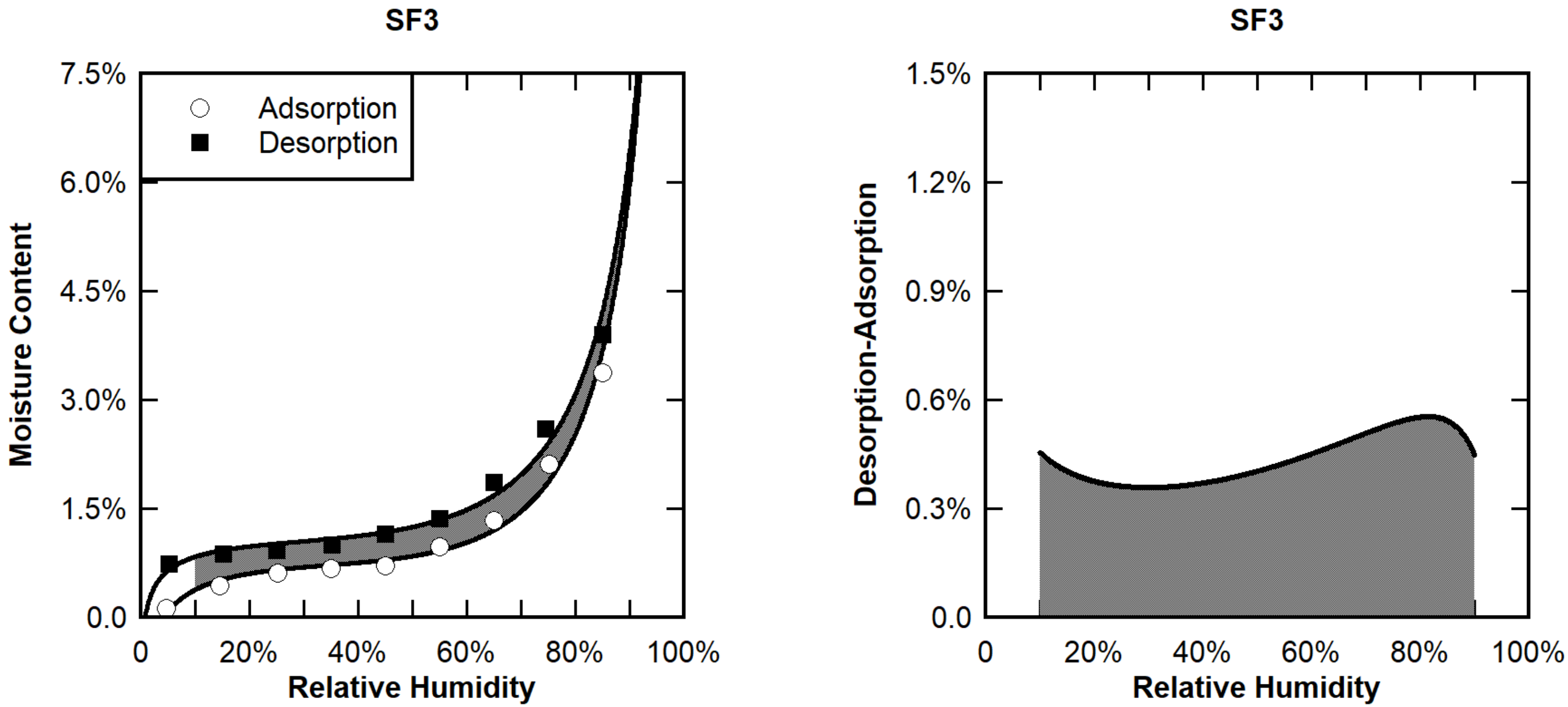
Estimating Absorption Capacity

Approach #2 – Atmospheric Absorption



Estimating Absorption Capacity

Approach #3 – Dynamic Vapor Sorption



$$m = \beta_3[\ln(-\ln(RH))]^3 + \beta_2[\ln(-\ln(RH))]^2 + \beta_1[\ln(-\ln(RH))] + \beta_0$$

Estimating Absorption Capacity

Silica Fume	a_{SA} (%)	a_{AA} (%)	$a_{VF,NM}$ (%)	$a_{VF,100}$ (%)	$a_{VF,200}$ (%)	$a_{VF,500}$ (%)	$a_{VF,S}$ (%)	a_{DVS} (%)
SF1	18.1	6.4	121.9	115.9	95.2	94.5	38.6	0.121
SF2	14.8	20.6	198.2	159.5	149.2	147.3	64.6	0.107
SF3	22.4	52.2	63.5	58.7	57.5	59.7	38.7	0.348
SF4	20.5	23.0	192.4	168.9	145.6	152.3	64.1	0.075
SF5	18.6	29.2	67.3	68.1	57.7	57.6	68.9	0.761
SF6	24.0	29.9	73.0	53.4	51.3	67.7	47.0	0.368
SF7	26.2	36.9	60.3	47.3	46.6	56.7	32.0	0.132
SF8	23.8	---[a]	72.5	63.7	61.5	65.7	75.4	0.625

[a]Due to limited material supply, this test was not performed for SF8.

Estimating Absorption Capacity

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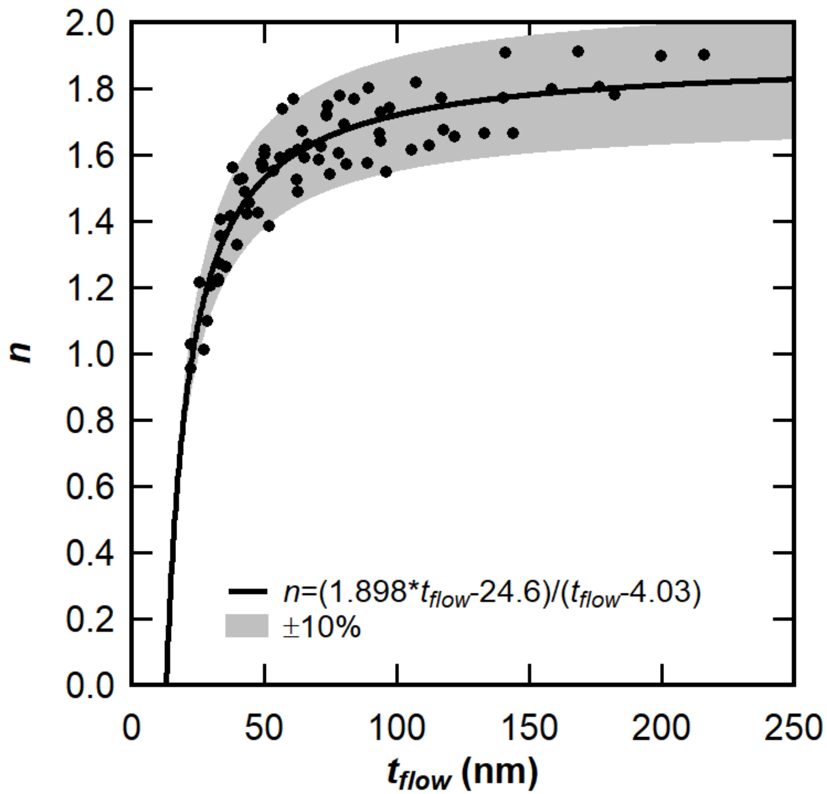
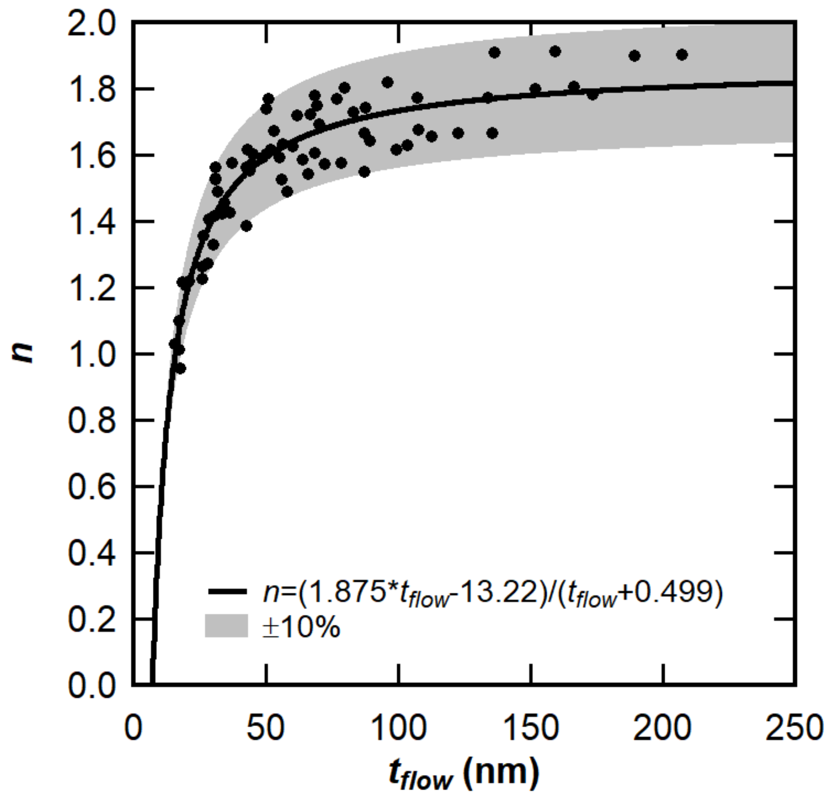
Water Thickness Model

No Absorption



Statistical Absorption



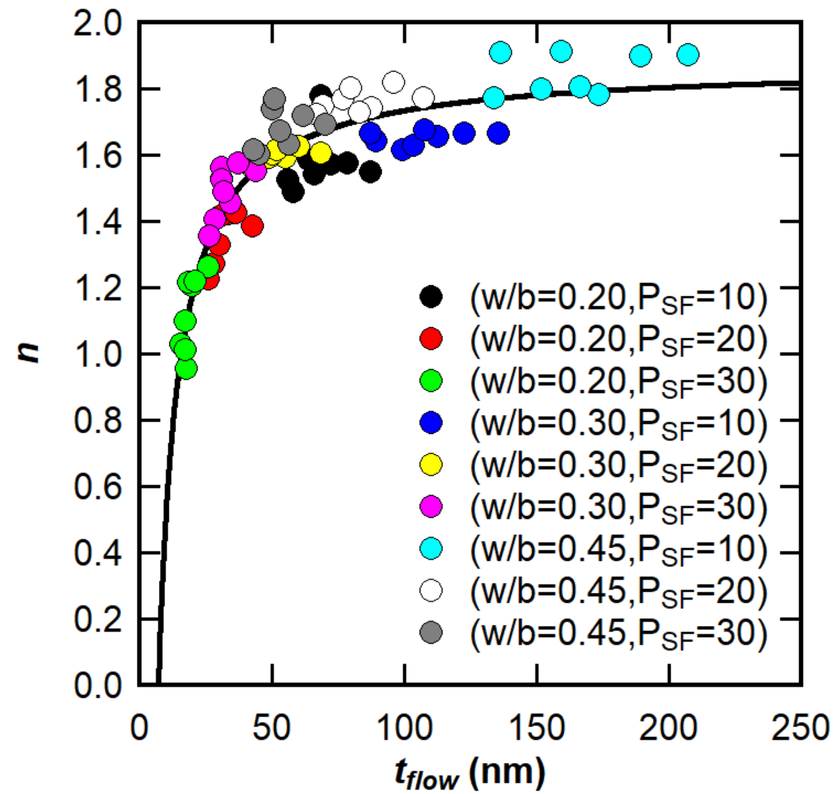
Water Thickness Model

Absorption	$R^2_{y=x}$	RMSE	MAE
No	0.815	0.085	0.072
Yes	0.826	0.083	0.069

Absorption	Range	RMSE	MAE
No	< 40 nm	0.090	0.079
Yes	< 40 nm	0.076	0.064
No	≥ 40 nm	0.084	0.070
Yes	≥ 40 nm	0.086	0.071

Water Thickness Model

Segmented by w/b and Silica Fume Content



Conclusions

- **Different silica products react differently, with a factor of 2.5 between low reactivity and high reactivity silica fumes.**
- **Statistically, the specific silica fume used in a mixture proportion significantly affects the ease of mixing.**
- **Silica fume particles are absorptive, with a factor of as much as 10 between low absorption and high absorption silica fumes.**
    - **It is critical to consider this absorption when proportioning low w/c concretes like UHPC.**

- **All silica fumes are not the same, and we cannot treat them as if they were!**

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[1]American Concrete Institute, “ACI CT-18 ACI Concrete Technology,” American Concrete Institute, Farmington Hills, MI, 2018.

[2] H.G. Russell and B.A. Graybeal, “Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community,” Federal Highway Administration, McLean, VA, 2013.

Publications

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- J.F. Burroughs, J. Weiss, and J.E. Haddock, “Influence of high volumes of silica fume on the rheological behavior of oil well cement pastes,” Construction and Building Materials, vol. 203, pp. 401-407, 2019.
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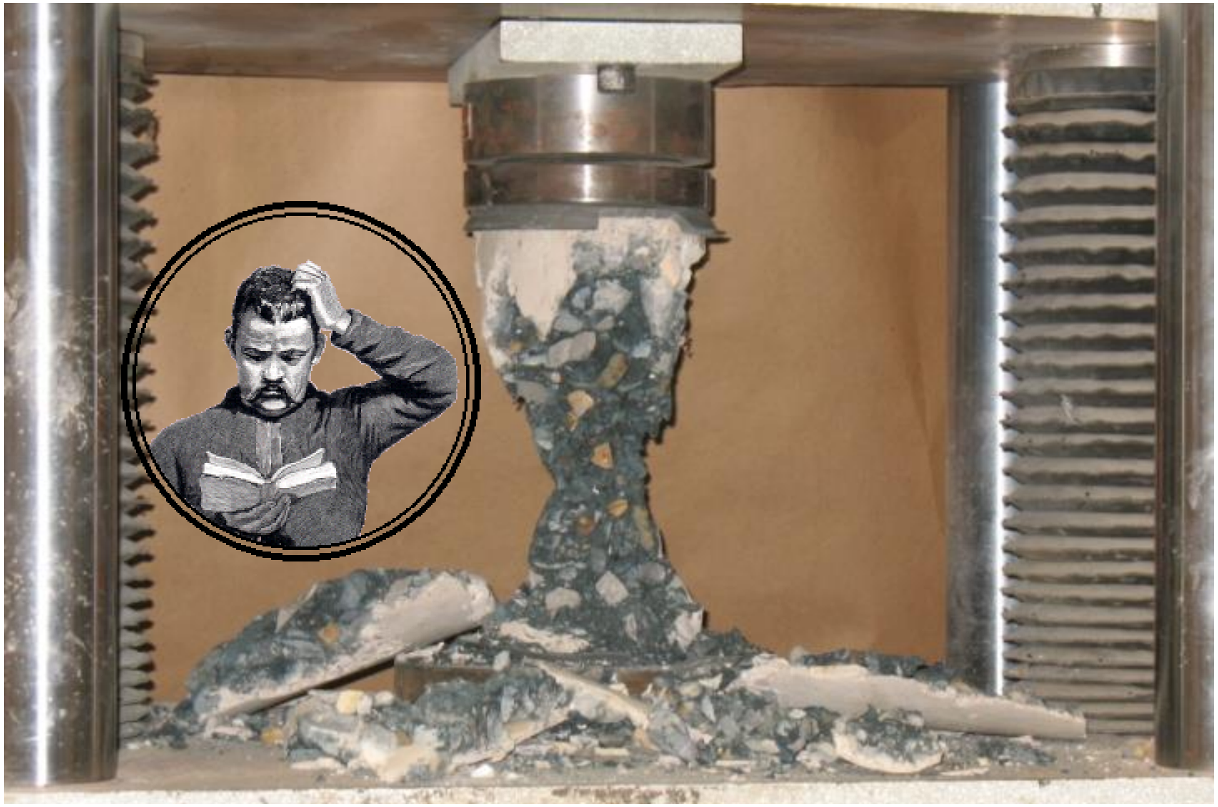
Acknowledgements

- Permission to publish was granted by the Director, Geotechnical and Structures Laboratory.



QUESTIONS ?

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